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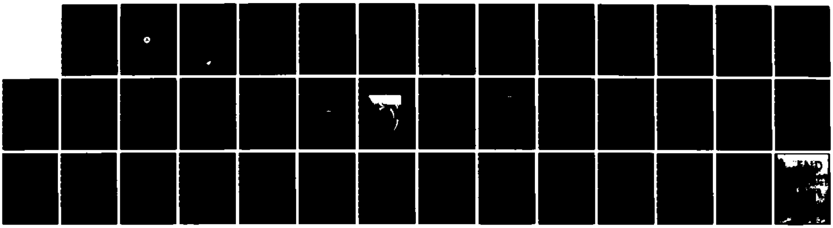

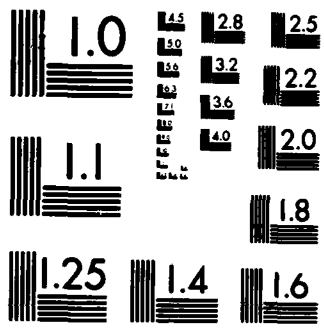

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REPORT NO: CG-D-23-84

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A METHOD FOR EVALUATING SMOKE CONTROL ON SHIPS USING SF_6 TRACER GAS

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Final Report

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16. Abstract

This study was the first of a series whose overall objective is to evaluate the possibility of applying smoke control techniques to Coast Guard cutters. A technique was developed that can determine the movement of room temperature air by using the easily detectable tracer gas sulfur hexafluoride (SF_6). The supporting equipment is transportable and field operational. Evaluation of the technique demonstrated under field conditions on an operational CG cutter that quantitative data on air flow characteristics of ventilation systems can be obtained. All tests were conducted on the 210 foot USCGC VIGOROUS at the U.S. Coast Guard Academy in New London, Connecticut.

Test results indicated that SF_6 can be easily and effectively used to show the air transfer patterns of existing heating, ventilation and air conditioning (HVAC) systems. It can also be used to test for watertight integrity and identify critical areas in current ventilation systems. Further work needs to be done with this technique to correlate cold air movement with hot air movement. In addition to correlating the present technique, future work would modify the technique in attempts to closer simulate hot smoke movement.

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METRIC CONVERSION FACTORS

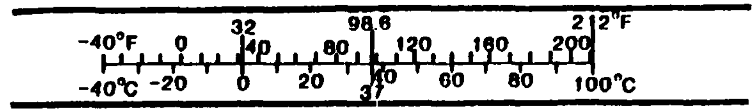
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

"This is not a drill--we have a fire in CPO Quarters--all hands muster on the flight deck." At approximately 0340 on 30 March 1977 USCGC MIDGETT (WHEC 726) sounded general quarters. "Smoke, heat and gas were carried throughout the ship by air-handling ducts, as the ship's ventilation service was not secured until 0434... Structural factors allowed the spread of smoke, flame and noxious gas to areas of the ship which were remote, and made it difficult to control the spread of fire or set up fire boundaries. Open stairways, ladder spaces and hatches developed flue-like openings where heat and smoke were free to travel the entire length of the ship, from pilot house to crew's berthing." These excerpts are taken from the Finding of Fact section of the investigation report following this tragedy. This fire resulted in the death of one crew member by asphyxiation secondary to smoke inhalation. A much less serious fire occurred on board USCGC JARVIS (WHEC 725) on 17 December 1976. It was started by an electrical short at a splice in the shore tie cable which was lying on the main deck. Before this fire was extinguished, smoke found its way through the fixed supply ventilation systems to the reefer flat, #3 auxiliary machinery room and the galley.

Between 1967 and 1978 there were 71 reported fires on board Coast Guard vessels including 29 on high endurance cutters and 22 on medium endurance cutters. Fortunately, very few fires resulted in personnel casualties. Nevertheless, the frequency of such occurrences requires a continual review of shipboard fire protection.

The ventilation system on post 1965 Coast Guard cutters allows an unblockable path for the flow of fire gases. Currently, the fire fighting technique used on cutters is to shut down the heating, ventilation and air conditioning (HVAC) system when a fire is reported, thereby limiting the supply of air and isolating the area of involvement by setting fire boundaries. As was illustrated in the examples cited, the HVAC system is not always shut down in a timely manner. Even if the HVAC system were shut down immediately, the present fire fighting theory has a serious deficiency. Limiting the amount of oxygen available to the fire creates a smoldering fire that usually produces more smoke and oxygen depletion which increases both the danger to personnel and the time to locate the seat of the fire.

A different fire protection technique to emerge in recent years utilizes exhaust systems and smoke control. The first principle behind these two tools is that smoke from a localized fire must be vigorously vented before it envelopes occupants with choking gases. The second principle calls for a more complex design of ventilation systems that can create positive pressurization in areas used as escape routes such as stairwells, elevator shafts, and corridors around a fire. Smoke migration will be minimized in areas of higher pressure. These principles have been successfully demonstrated over the past 15 years in several buildings in Australia, Canada, Great Britain and the United States, and they are being incorporated into new building design.

Due to their highly compartmented decks and watertight construction, vessels seem ideal candidates for applying these smoke control techniques. However, applications of these principles have not been attempted on either merchant or naval vessels. There are indications that by using existing ventilation fans on vessels to vent the smoke from a fire, escape from and access to fires can be made more quickly. Of course, redesigning the ventilation system might allow an even safer escape and a faster access.

Before smoke control techniques can be used, it is necessary to understand smoke migration. The smoke produced by a fire will vary enormously both from fire to fire and from time to time in the same fire. It is, therefore, only possible to speak in broad terms about the smoke produced. The combustion products from a fire have many constituents which fall into three general groups:

(1) Hot vapors and gases given off by the burning materials.

(2) Unburned matter and condensate which may vary from light-colored to black and sooty.

(3) A quantity of air heated by the fire and entrained in the rising plume.

Not all of these constituents are visible. The smoke from most fires consist of a well-mixed combination.

The amount and quality of the smoke will depend both on what material is burning and the way in which it burns. For life safety, two aspects must be considered. First, smoke may impair both visual and respiratory functions elevating a person's anxiety level and respiration rate thus making escape more difficult. In addition, smoke contains toxicants such as carbon monoxide (CO) which is both colorless and odorless. Concentrations of CO as low as 0.1 - 0.2% will produce confusion of the mind, headache and nausea. Concentrations of 0.2 - 0.25% usually produce unconsciousness in about 30 minutes, and inhalation of higher concentrations can cause sudden, unexpected collapse with subsequent death.[1]

Since smoke usually contains hot gases, buoyancy is one of the two main factors that determine the movement of smoke from a fire. The second factor is the normal air movement due to temperature differentials, wind and the HVAC ventilation system. Although the ventilation system has nothing to do with the fire, it can provide a means of carrying smoke throughout the ship. It would be expected that buoyancy effects will dominate close to a fire, and as the distance from the fire increases, normal air movement will become dominant.

To determine the extent that smoke control techniques could be used on Coast Guard cutters, tests were conducted on the 210 foot USCGC VIGOROUS (WMEC 627) between the 17th and the 25th of March 1983. The ventilation system on this class of vessel is similar to that used on the high endurance cutters (378 foot cutters). A tracer gas was used to simulate smoke. The effect of the HVAC system on the movement of air, as indicated by the tracer gas, was studied under various closures and fan speeds. Once satisfied that the results were reproducible, several tests were conducted to isolate the tracer gas by manipulating the closures and fan settings.

2.0 OBJECTIVES

The objectives of this test program were:

a) to develop a technique that could determine the movement of smoke aboard a vessel.

b) to evaluate this technique aboard an operational CG cutter.

3.0 PRESSURE MAPPING

One of the principles of smoke control requires a ventilation system that can create positive pressurization in areas used as escape routes. This requires that the ventilation system be able to create a higher pressure than the pressure a fire creates in a compartment. It was found that the overpressure of a fire ranges from 0.10 inches of water for an open door compartment to 0.25 inches of water for a closed door compartment[2]. Therefore, it was necessary to determine if the present ventilation system on the 210 ft cutters is capable of creating the pressure differential required to effectively control smoke.

The initial step in this study was to determine the airflow between various shipboard spaces due to pressure differentials. Since there is almost an infinite number of combinations for the closure configurations, it was not possible to study all of them. Additionally, the 210 ft cutters have 10 supply ventilation systems, 9 exhaust ventilation systems and 1 recirculation system. Each system has a fan and each fan has a high, low and off setting. It was decided to study the three most common configurations of the closures. These were determined to be the normal configurations when the vessel is in port, underway, or at general quarters. The individual closure positions for each of these configurations are listed in Table 1.

Figures 1 and 2 show the main deck and the second deck of the fore part of CGC VIGOROUS. The axis at the bottom of each figure shows the ship's frame numbers. All areas on the main deck and below between frames 32 and 108 are served by a supply blower located on the main deck starboard side at frame 65. The areas between frames 52 and 108 are served by an exhaust blower located on the main deck port side at frame 117. The supply ducts run into each toilet and shower area and into each recirculating unit as replenished air. The recirculating units are located in all berthing spaces for either heating or cooling. During this project, the recirculating units were on the heat cycle. Exhaust ducts draw from each toilet and shower area. Since this section of the vessel is predominately berthing compartments, it was considered an area of primary importance for smoke control studies.

Every section of the vessel is modified to some degree by the sections adjacent to it. The section forward of the berthing area begins at frame 32 and is served by a supply and an exhaust blower on the 01 deck forward at frame 10. Both supply and exhaust ducts run to each compartment in this area. There are no recirculating units.

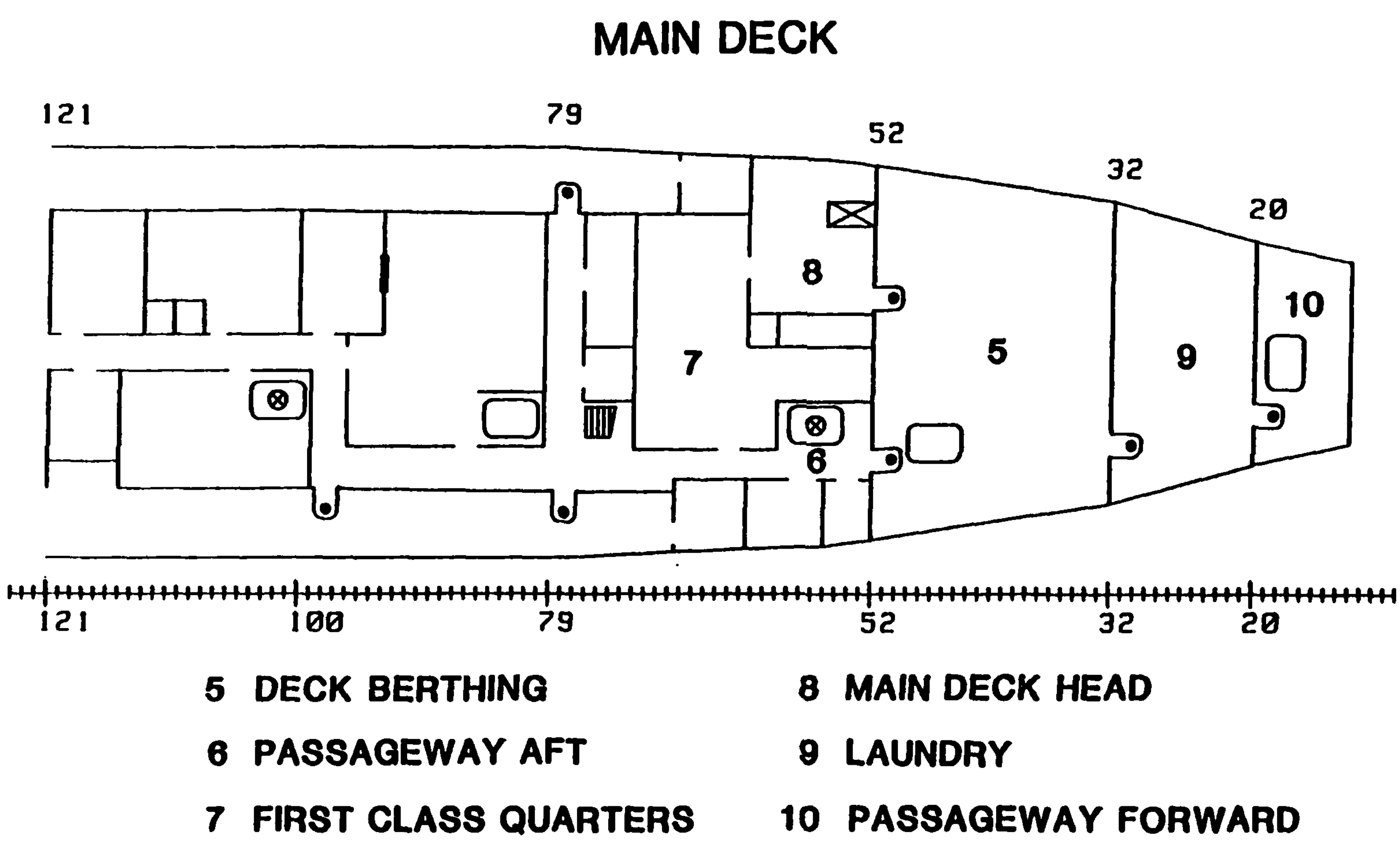
Eleven of the twenty one planned test modes for pressure mapping were completed for the berthing section. These were conducted 8-11 February and are listed in Table 2. The section immediately forward of the "Berthing" section is labeled "Laundry" and the area immediately aft is labeled "Scullery."

Using differential pressure gauges, the differential air pressure in adjoining spaces in the three areas was measured. Two pressure gauges were

TABLE 1
FITTINGS AND CLOSURES CONFIGURATIONS

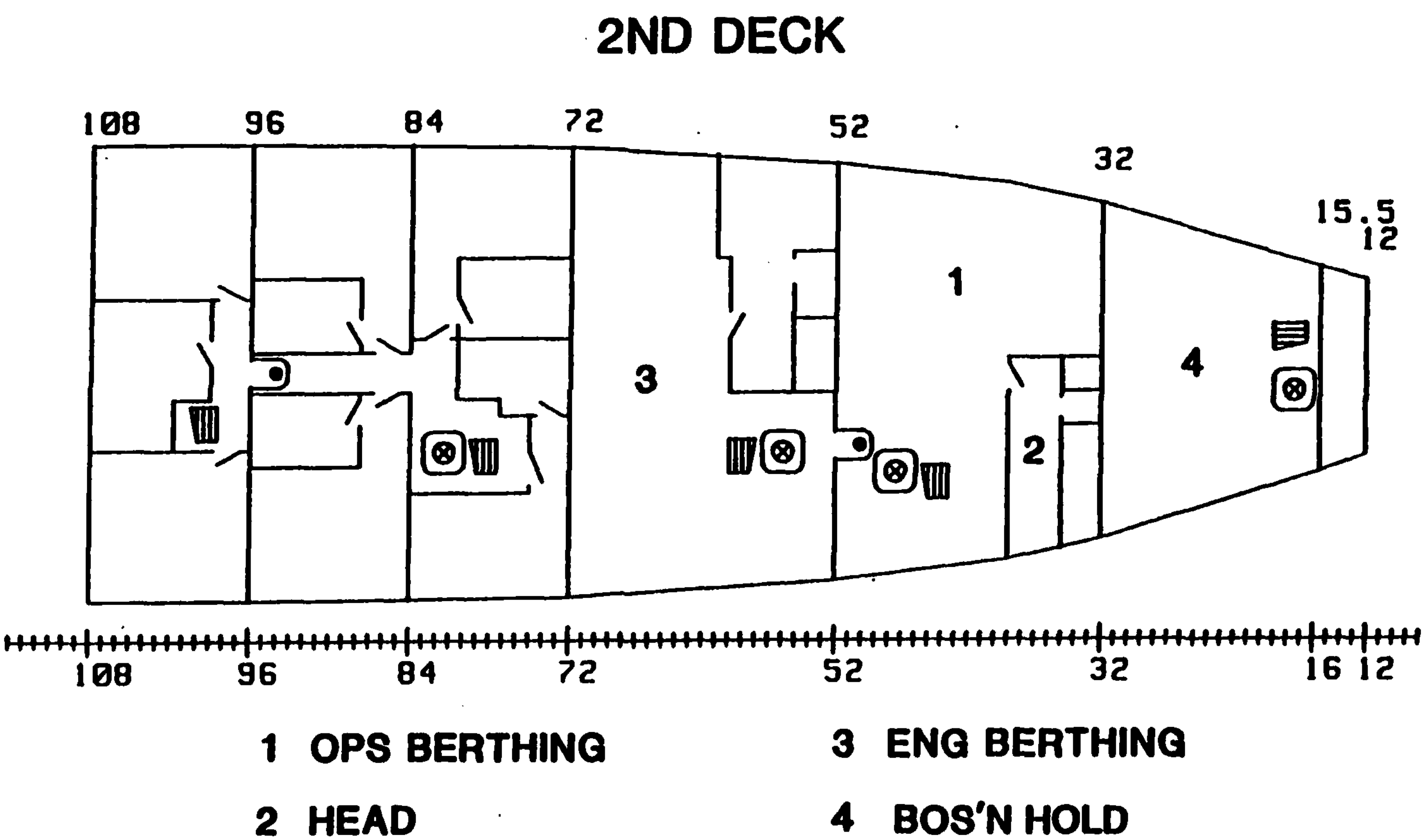
Fitting	Location	In Port	Underway	General Quarters
		CONFIGURATION		
WTH 01-15-0	From 01 deck to upper passageway	X	X	X
WTD 1-12-1	From upper passageway to forward stores	X	X	X
WTD 1-20-1	From upper passageway to laundry	X	X	X
WTH 2-16-4	From Bosun Stores to paint locker	X	X	X
WTD 1-32-1	From laundry to to Deck berthing	X	X	X
WTD 1-52-2	From Deck berthing to main deck head	X X	X X	X X
WTH 2-45-1	From Deck berthing down to Engineers' stores	X X	X X	X X
WTD 2-51-2	From Deck berthing to Engineer berthing	X	X	X
WTH 2-59-1	From Engineering berthing to magazine spaces	X	X	X
WTH 2-80-1	From Wardroom staterooms to I.C. and gyro room	X	X	X
WTD 2-96-0	From Wardroom staterooms to CPO staterooms	X	X	X
All WT Weather Doors		X	X	X
WTD 1-52-1	From Beck berthing to the passageway aft	O	X	X
WTH 1-59-1	From the passageway aft to Engineering berthing	O	X	X
WTH 1-59-1 (scuttle)		X	O	X

Key: WTH = Watertight hatch
WTD = Watertight door
O = Open
X = Closed



MAIN DECK PLAN OF CGC VIGOROUS

Figure 1



SECOND DECK PLAN OF CGC VIGOROUS

Figure 2

Table 2

PRESSURE MAPPING TEST MODES

Test Numbers	Configuration	Fan Settings: Laundry Supply	Laundry Exhuast	Main Supply	Main Exhuast	Scullery Exhaust
1	Inport	High	Off	High	Off	Off
2	General Quarters	Low	Low	Low	Low	Low
3	Inport	High	High	High	High	Low
4	Underway	High	High	High	High	Low
5	Underway	Off	Off	Off	Off	Low
6	Inport	High	High	Low	High	High
7	Inport	Off	High	Off	High	High
8	Underway	Off	High	Off	High	High
9	General Quarters	Off	Off	Off	Off	Off
10	General Quarters	Off	High	Off	High	High
11	General Quarters	Low	Low	Low	Low	Low

used for the measurements. One gauge had a range of 0 - 0.25 inches of water and the other one had a range of 0 - 1.0 inches of water. The pressure differentials were taken by inserting a small tube across a boundary under a non-tight door, through an open test hole, or through a barely opened door. It is recognized that the latter measurement was not a true difference in pressure since the open crack allowed an air flow which began to equalize the pressure. However, it gave the direction of the air flow and an idea of the magnitude of the pressure across the boundary since the true pressure was higher than the measured ones. Pressures exceeded 0.25" of water across several boundaries under different closure configurations and fan settings. From the data pressure "maps" of the various shipboard spaces were developed. One of the results giving the greatest differences in pressure occured in Test 10 for the deck berthing area. This is illustrated in Figure 3. The directions of the arrows indicate the flow of the air and the numbers indicate the pressure in inches of water. The figure shows that the pressure differential is greater than 1" of water which is more than enough pressure to contain smoke in that compartment. However, it must be remembered that these are preliminary findings that have not yet been reproduced.

4.0 TRACER GAS TECHNIQUE

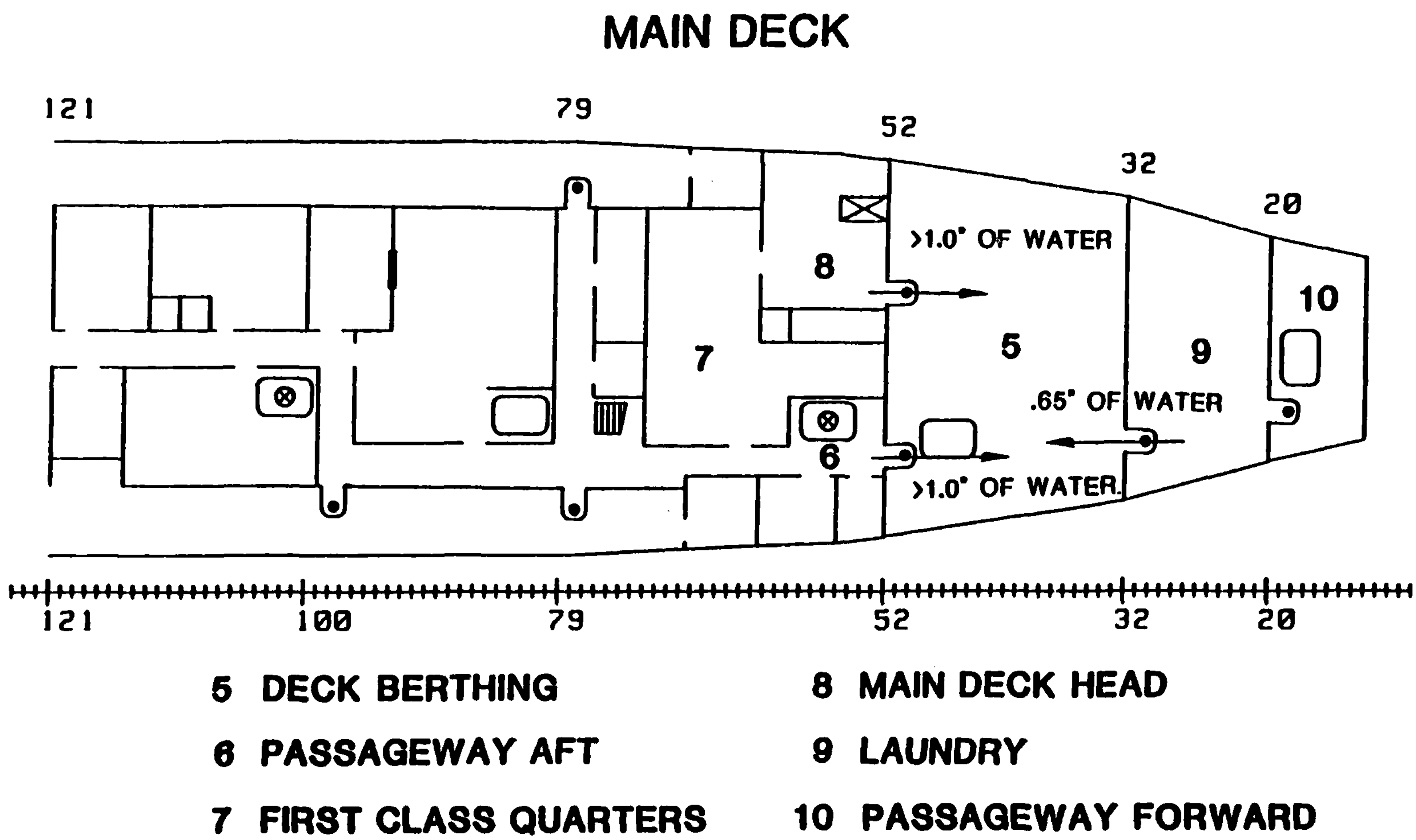
4.1 Characteristics of SF_6

Sulfur hexafluoride (SF_6) was the tracer gas selected to follow the air movements. This gas is colorless, odorless and easily detectable at levels down to one part per billion (ppb) by an electron capture detector. It has a molecular weight of 146.05 and a density at 70° F and 1 atm of 0.382 lb/cu ft making it about five times as dense as air. Its viscosity at 88° F is 0.0157 cp, a low value that makes it suitable for a gas-air tracer. The Threshold Limit Value (TLV) is a measure of toxicity. The TLV for exposure to SF_6 is 1,000 parts per million (ppm). The gas has, in fact, been described as a physiologically inert gas. Rats have been exposed to the maximum concentration of SF_6 possible without lowering the oxygen supply to an unsafe level (80% SF_6 and 20% O_2) for periods of 16-24 hours. The rats showed no sign of intoxication, irritation or any other toxic effect, either during exposure or afterward. Since there is no health danger to personnel, SF_6 could be used on an operational Coast Guard cutter, and the air movement could be traced without greatly disrupting shipboard routine. The concentration of SF_6 during the actual tests never exceeded 5ppm and most of the time was under 200 ppb.

Sulphur hexafluoride is an extremely stable gas. It does not react with water, alkali hydroxides, ammonia or hydrochloric acid. It is noncorrosive to any metal at ambient temperatures. Additionally, it is nonignitable and nonflammable. One of the largest uses of SF_6 is in gas-filled circuit breakers. It is also used in gas insulated transmission lines and electrical power-distribution substations. None of these are found in a normal shipboard environment. Hence, contamination of test samples from other SF_6 sources were minimal.

4.2 Methods of Testing and Instrumentation

Two series of tests were run and the SF_6 was released from a different location for each series. To simulate the worst location for a



PRESSURE MAP OF DECK BERTHING COMPARTMENT

Figure 3

berthing area, the SF_6 was released from the forward port side of the lowest, most forward berthing area (indicated as (1) in Figure (2)). The other release area used was the center of the paint locker. Six tests were run releasing the SF_6 from the berthing area and three were run releasing the SF_6 from the paint locker.

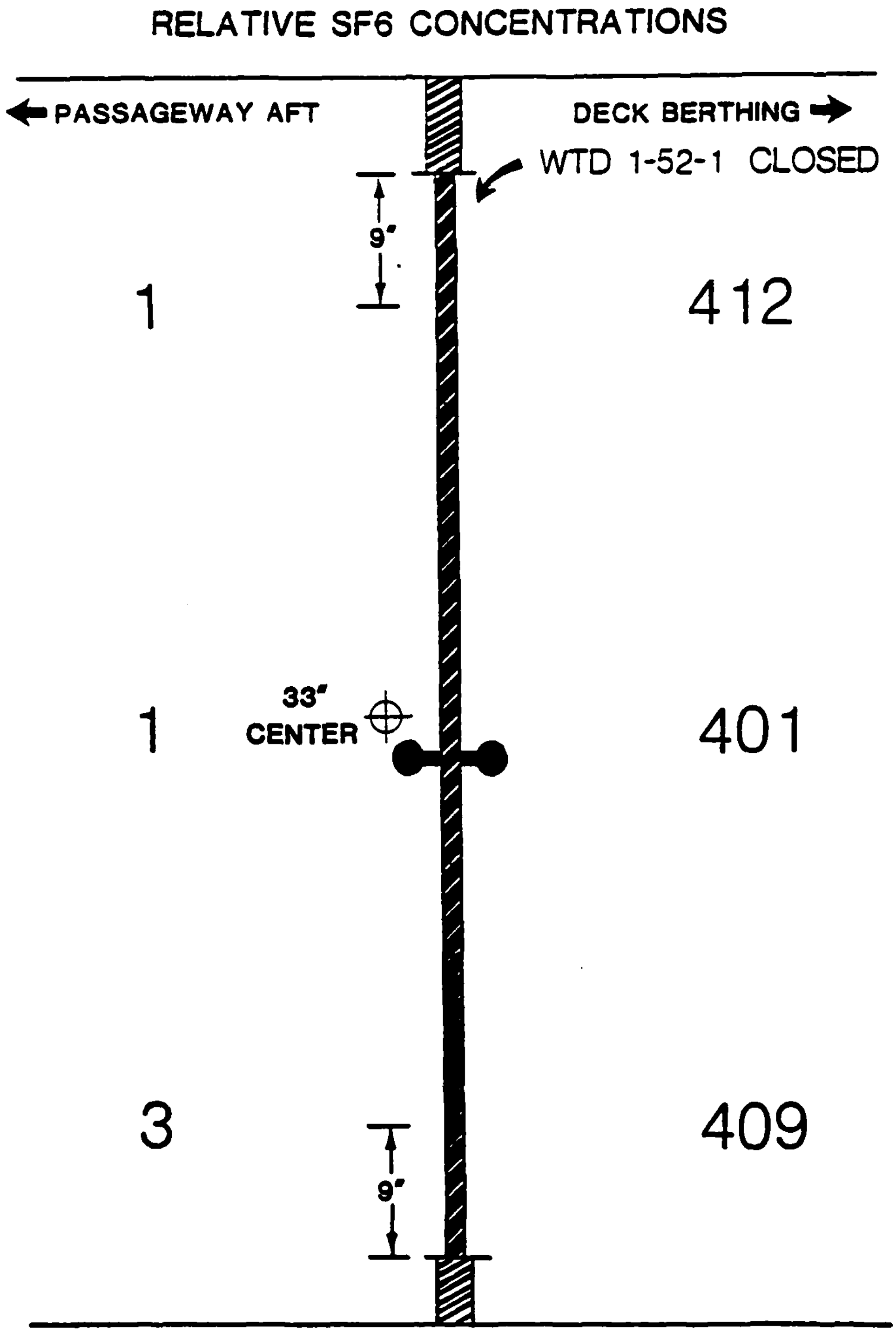
The SF_6 was released from a 0.015 cu ft. cylinder at a flow rate of 3-5 ml/min for a 30-minute period. The 30-minute period commenced five minutes after the start of each test. A release rate of 4.5 ml/min was determined to yield good test results.[3] This release rate provided a well mixed and evenly distributed concentration of SF_6. It was low enough so that it did not saturate the detector yet high enough to still be detectable for low concentrations in remote locations. The flow rate of SF_6 was regulated by a flow meter that could be set to release gas in the range of 3-27 ml/min. Fifty milliliter air samples were taken with disposable syringes at 60 inches above the deck by a team of three samplers. In locations where a rapid change in concentration was anticipated, samples were taken at 5 minute intervals. In all other locations samples were taken at 15 minute intervals. This is reflected in graphs 7-15. If the first sample was taken just prior to the release of the SF_6 the concentration curve begins at zero. However, if the sample was taken after the SF_6 release had commenced the curve starts at a relative concentration greater than zero.

For each test, between 80 and 125 samples were taken. The samples were capped, marked, and brought back to a central room to be analyzed. The concentration of SF_6 in the air samples was measured by a portable gas electron chromatograph. It was fitted with a 0.25 ml sampling loop and a capture detector with a 200 ml tritium source. The instrument was calibrated before and after each test by standard SF_6/air mixtures. The output of the instrument was recorded by a reporting integrator.

4.3 Technique Verification

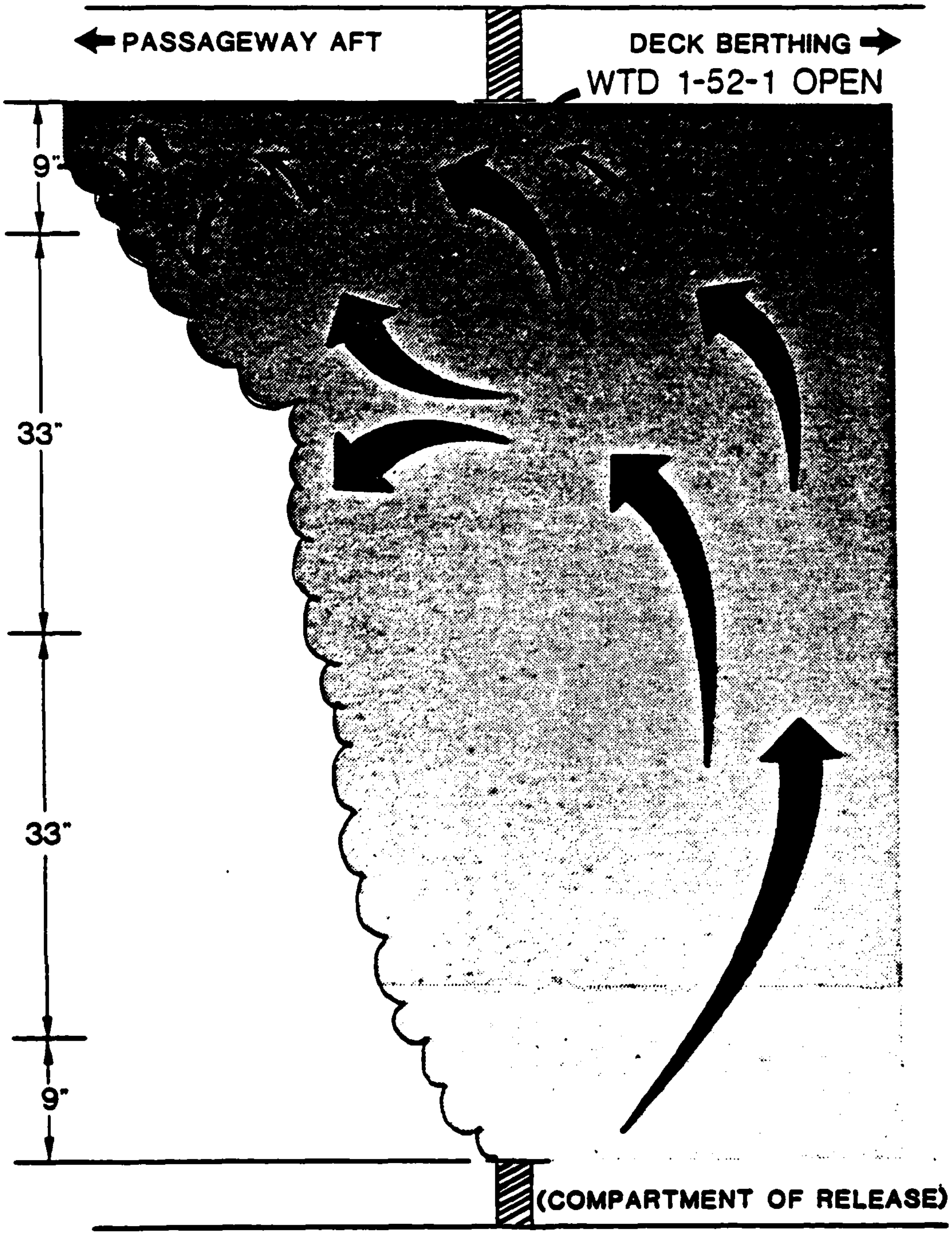
Sulfur hexafluoride was used as an air tracer. A good tracer should be well mixed with the fluid it is tracing. In order to determine how well mixed the SF_6 was in a compartment the following test was conducted. A concentrated amount of SF_6 was released in one compartment, while the adjacent compartment had a very low concentration of SF_6. The two compartments were separated by a water tight door. Samples were taken in each compartment vertically and horizontally, and the results are displayed in Figure 4. The compartment with the concentrated amount of SF_6 appears on the right side of the figure and the compartment with very little SF_6 is shown on the left side. The figure illustrates two points, the first one is that the SF_6 was evenly distributed and well mixed. Secondly, the water tight door was effective at confining the SF_6, for at least the duration of the 40 minute test.

If the compartment on the right side of Figure 4 contained hot smoke instead of SF_6 and the door between the two compartments was opened, the phenomenon that might occur is depicted in Figure 5. Hot smoke, driven by buoyancy and temperature differentials, would exit out the top of the opening of the door as the cool air enters at the bottom. However, the compartment contained SF_6 which is colorless. Also, it was at room temperature and not as hot as combustion gases would be. Nevertheless, it was desired to know how



UNIFORM MIXING OF SF_6

Figure 4



HOT SMOKE THROUGH AN OPEN DOOR

Figure 5

the SF_6 would behave if the door were opened. The door was opened and samples were taken at three different heights. The results are illustrated in Figure 6. Knowing that the temperature differentials were not great and that SF_6 is about five times as dense as air, it might be expected that the SF_6 would settle in the lower part of the compartment. However, the results show behavior similar to hot smoke. This illustrates just how sensitive this tracer gas is to small air currents.

Each air sample took two minutes to be analyzed by the gas chromatograph. Since there were between 80 and 125 samples taken for each test, some samples would be in the sample syringe a considerable period of time before they were injected into the analyzer, there were some concerns that SF_6 might dissipate while awaiting analysis. To address this, two samples were taken in the same location at the same time. One was analyzed immediately, the other was left in the sample syringe for 24 hours and then analyzed. The results were identical. Consequently, it was concluded that the wait for analysis did not affect the samples.

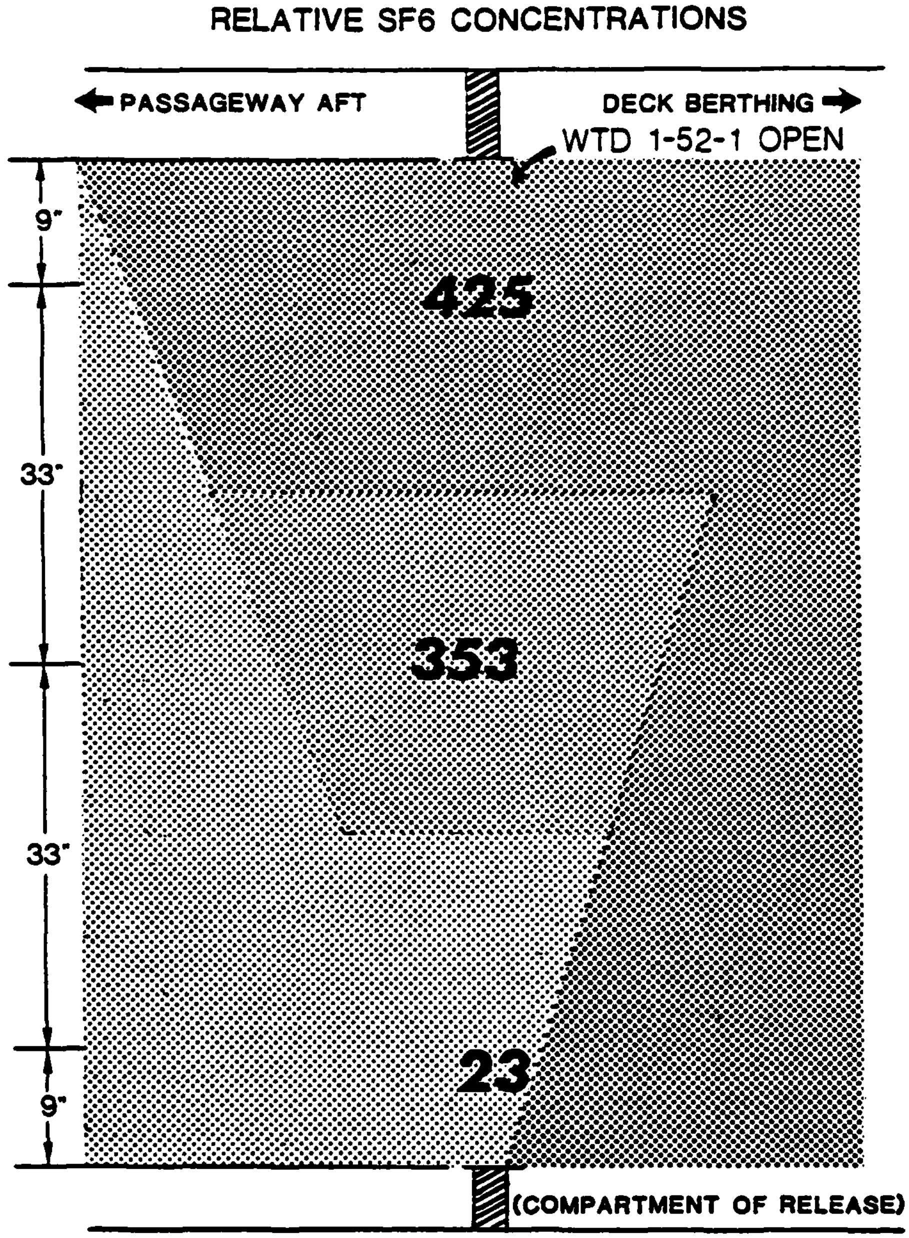
5.0 TESTS ON USCGC VIGOROUS

5.1 Preliminary Tests

Preliminary Trial A was conducted with the SF_6 being released from the berthing area. To determine the air transfer patterns for the vessel when it is in port, the normal ventilation conditions for "in port" status were set. Both supply and exhaust fans were operated at low speed and the watertight doors and hatches were placed in the positions indicated under the "In Port Configuration" column in Table 1. Samples were taken as discussed under the "Methods of Testing" section and the data recorded.

Preliminary Trial B was run with the conditions identical to the first preliminary trial and the resulting data were compared with the first trial. The time to reach maximum concentration of SF_6 and the concentration of SF_6 at that time were the same for corresponding locations. Additionally, concentrations of SF_6 at all other corresponding times were the same for the corresponding locations. This confirmed the reproducibility of the tests and provided the confidence for both the subsequent data and the time interval for sampling. The tests indicated that sampling at 5-minute intervals was appropriate in locations where a rapid change or fluctuation was expected and 15-minute interval sampling was sufficient at all other locations.

Preliminary Trial C was run simulating an emergency condition. Both supply and exhaust blowers were turned off and the access fittings were positioned as indicated under the "General Quarters Configuration" column in Table 1. Sample results showed no appreciable amounts of SF_6 anywhere. Forty-five minutes into the test WTD 1-52-1 from deck berthing into the passageway aft was opened and remained open to simulate a repair party entering. SF_6 showed up within 15 to 30 minutes in the passageway aft, 01 deck passageway, the wardroom, staterooms, engineering berthing and the engineering toilet and shower area.



SF_6 THROUGH AN OPEN DOOR
Figure 6

5.2 Berthing Compartment Series

After the preliminary trials were completed, two series of tests were developed. Both series were designed to compare the effect of different configurations and fan settings on limiting the movement of SF_6. A summary of these tests and the primary action taken appears in Table 3. All the tests are identified in this table by the date they occurred in addition to a test number.

For the first series of tests, the movement or confinement of SF_6 would be studied as it is affected through the manipulation of just one variable. The watertight door (WTD) at frame 52 was chosen as the variable.

The first series was conducted with SF_6 released from the berthing area. The first test was run at "General Quarters Configuration" on 20 March. Both blowers were initially on low speed. Ten minutes into the test the supply fire damper was closed eliminating supply air to the SF_6 release area. The exhaust blower was then restarted at the low speed. This created a pressure differential between the release compartment and those surrounding it. At 55 minutes into the test WTD 1-52-1 was opened and remained open to simulate a repair party entering. The second test was run on 21 March with the fittings positioned as indicated under the "Underway Configuration." The supply and exhaust blowers were left on the low speed, the fire dampers were left open, and WTD 1-52-1 remained open for the entire test.

On 24 March the third test was run with the fittings in the "General Quarters Configuration" and both supply and exhaust blowers on low speed. Ten minutes into the test the blowers were shut off and the supply damper was closed. Twenty minutes into the test both the supply and exhaust fans were restarted at the low speed. Since the supply damper to the release area remained closed, the release area was in the exhaust only mode. The compartments around the release area were both being supplied and exhausted with the aid of the blowers. Again, this created a pressure differential. This test differed from the first test in that in the fourth test the supply fan was off. This test was designed to see the effects of the supply fan on the pressure differential. At 45 minutes into the third test WTD 1-52-1 was allowed to be opened to enter deck berthing but, unlike the first test, was kept closed between openings. The door was opened in excess of 100 times during the last 85 minutes of the test. The results of these three tests are graphically depicted in Figures 7-11.

5.3 Paint Locker Series

In the second series of tests attention was turned to the effect that supply dampers have on the movement of air. A different section of the vessel was used for this series of tests. The ventilation system for this section of the vessel has its supply intake located in the focsle on the starboard side. The exhaust is in a corresponding position on the port side. The paint locker was chosen as the release area. It is located directly below the bosun hole shown in Figure 2. A scuttle separates the two compartments. An open ladder leads from the bosun hole up to the passageway forward of the laundry. A WTD separates the laundry from the passageway forward of it.

Table 3

SUMMARY TABLE FOR TEST SERIES

Test Number	Test Date	Release Area	Principal Action
BC 1	3/20	Berthing Compartment	WTD 1-52-1 opened at minute 55
BC 2	3/21	Berthing Compartment	WTD 1-52-1 left open
BC 3	3/24	Berthing Compartment	WTD 1-52-1 open and closed after minute 55
PL 1	3/22	Paint Locker	Supply damper closed, WTD 1-20-1 opened at minute 70
PL 2	3/23	Paint Locker	Supply damper left open
PL 3	3/25	Paint Locker	WTD and damper closed

The two variables manipulated in this series were the WTD between the laundry and the passageway forward and the supply damper to the paint locker. All tests were conducted to simulate actual fire conditions. When an actual fire is detected in the paint locker both the supply fan and the exhaust fan are secured. There is a butterfly valve damper in the supply duct that is also closed and carbon dioxide is then released in the compartment. No one is permitted to enter the paint locker for a least one half hour after the compartment has been flooded with CO_2. This minimizes the possibility of introducing oxygen which might trigger a reflash. The route a repair party would take is normally from the laundry through WTD 1-21-1 into the bosun hole and down to the paint locker. When a repair party does enter the paint locker, the exhaust and supply fans are set on high speed to remove smoke from the compartment. To simulate this chain of events, when the SF_6 was released in the paint locker, the exhaust and supply fans were secured. When the paint locker was opened about 60 minutes later, both supply and exhaust fans were engaged and operated at the high setting.

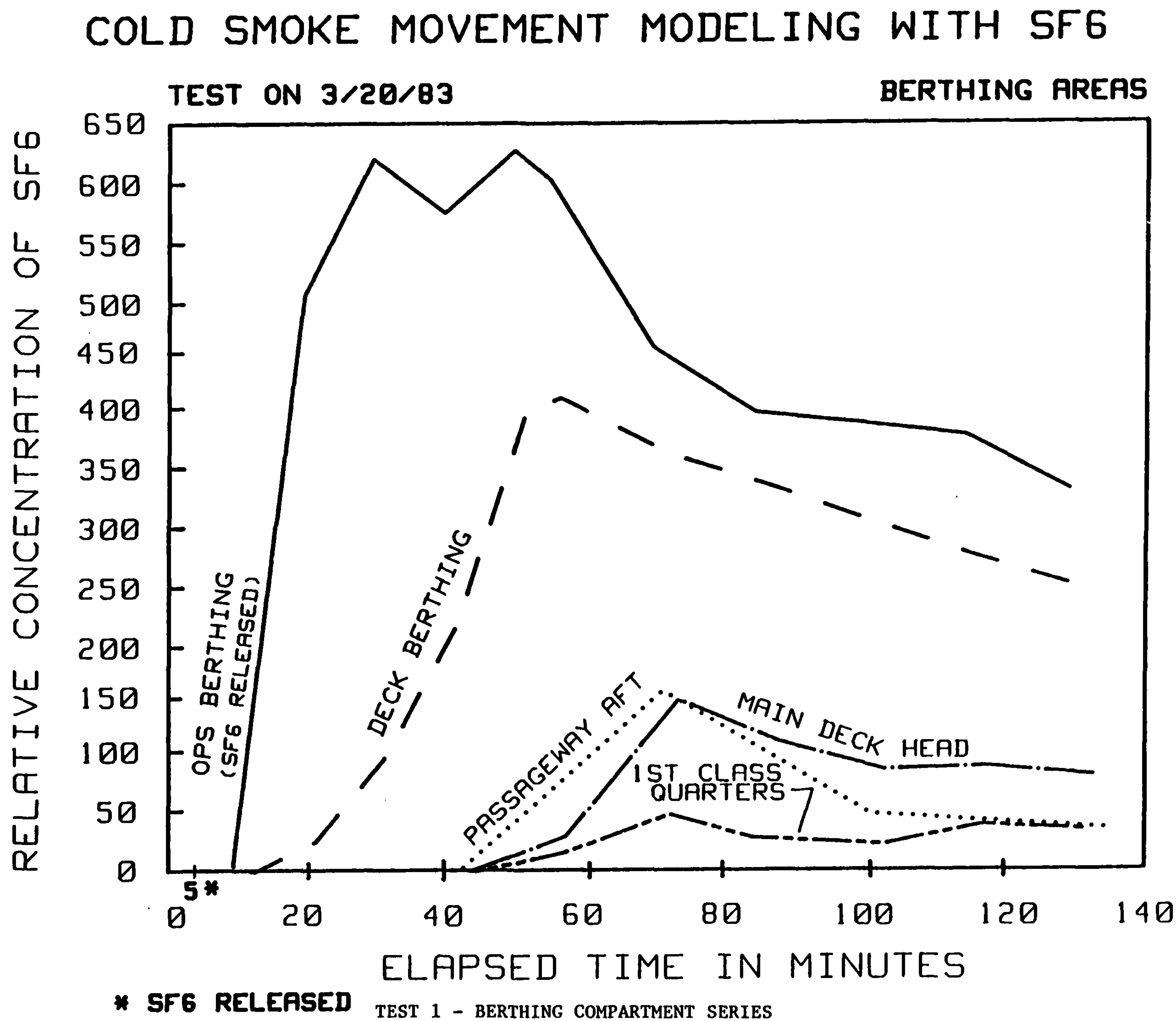
The first test was run on 22 March. The butterfly valve damper was in the closed position as was WTD 1-20-1. Sixty minutes into the test WTC 1-20-1 was opened and remained open for the rest of the test. On 23 March the second test was run with WTD 1-20-1 closed for the entire test. However, the butterfly valve damper was set in the open position for this entire test. The third test, run on 25 March, was conducted with both WTD 1-20-1 and the butterfly valve damper in the closed position for the complete test. The results of these three tests are graphically displayed in Figures 12-15.

6.0 RESULTS

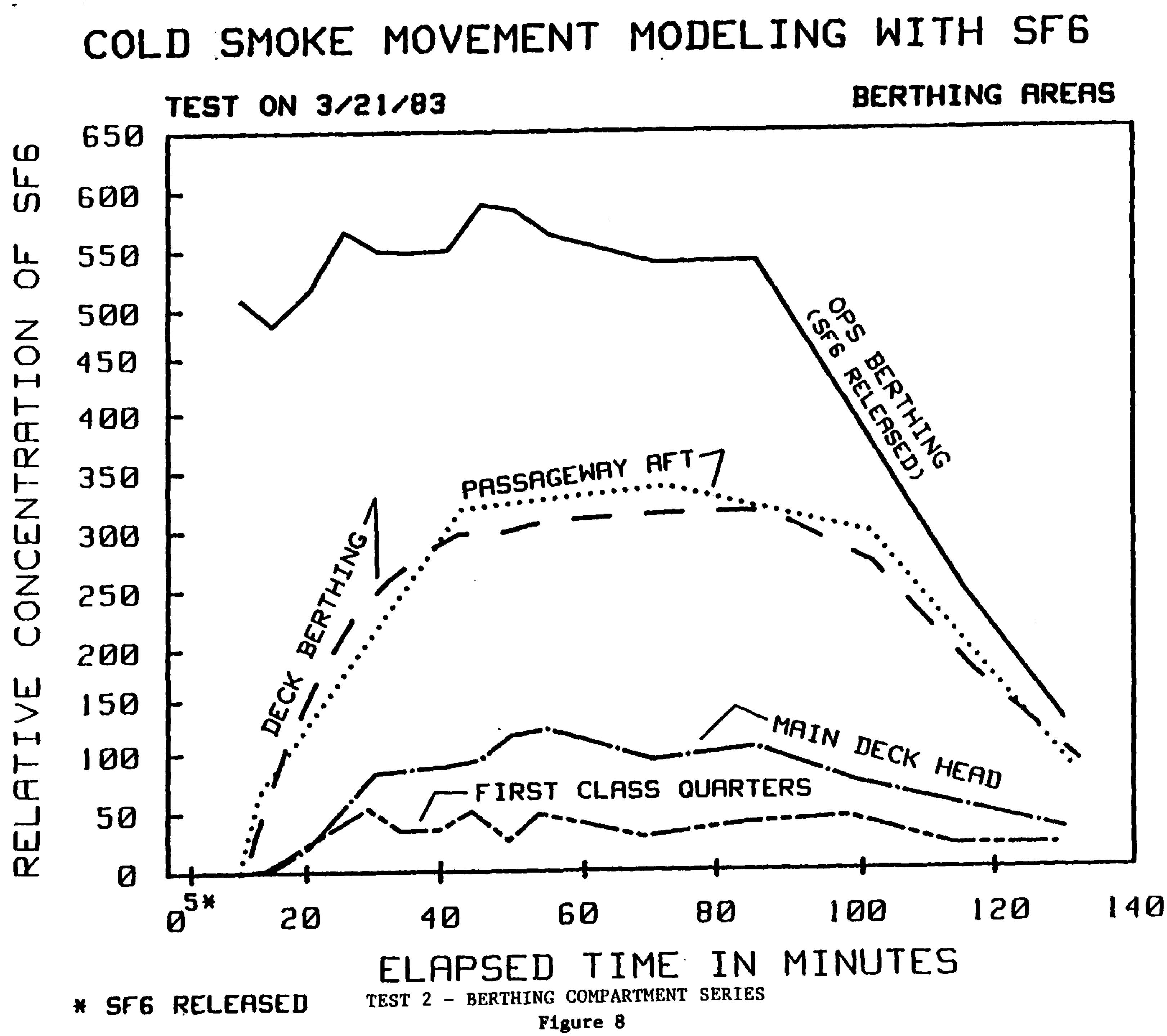
Figure 7 graphically depicts the results of the test conducted on 20 March. This was the first test run with the SF_6 released from the berthing area. For the purpose of clarity, only four sample locations, in addition to the release location of the SF_6, are shown on the graph. The locations shown are deck berthing, the passageway aft of deck berthing, first class quarters and the main deck head. The relative concentration of SF_6 detected is plotted against time.

Figure 7 shows that SF_6 appears in deck berthing at a steadily increasing rate and the curve generally follows the SF_6 concentration curve for operations berthing but with a time lag. Due to the open ladder between the two compartments, this would be expected. The other three locations, first class quarters, main deck head and the passageway aft, have negligible amounts of SF_6 until 55 minutes after release when WTD 1-52-1 was opened. The SF_6 then appears in these three compartments. However, there is a surprise. The concentration of SF_6 in the main deck head is greater than the concentration in first class quarters. This was not expected. The concentration of SF_6 was logically expected to decrease as it flowed or diffused from its origin to each successive compartment.

The results of the second test run in this series is illustrated in Figure 8. This graph shows that SF_6 appeared in significant quantities in all compartments. There are notable differences in the amounts that appeared in the various compartments and the time that they began to be detected. For example, in the passageway aft, the presence of SF_6 is noticed almost immediately upon release of the SF_6 and the concentration peaks about 45



TEST 1 - BERTHING COMPARTMENT SERIES
Figure 7



TEST 2 - BERTHING COMPARTMENT SERIES

Figure 8

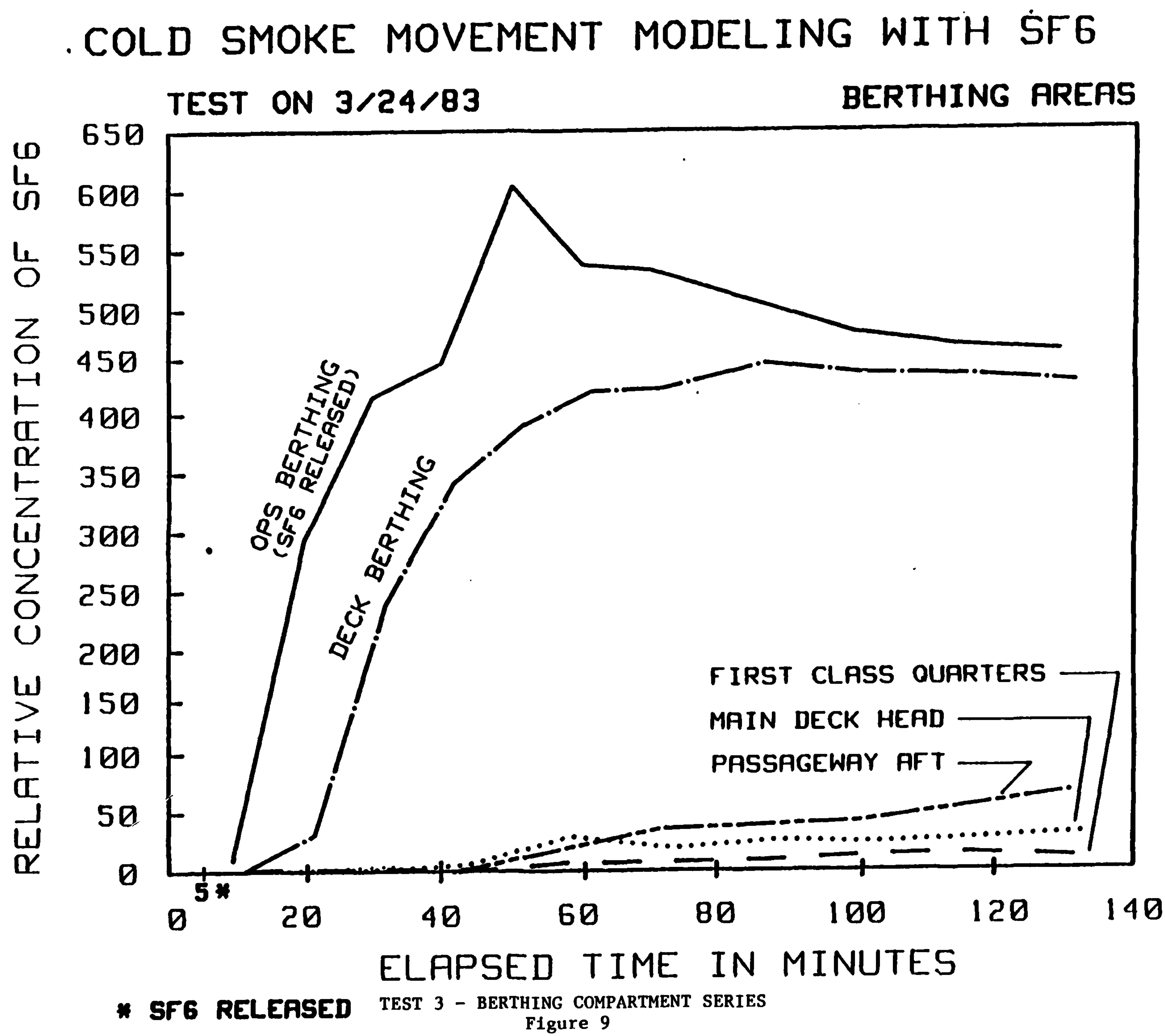
minutes after the release. However, in the main deck head, the SF_6 isn't noticeable for nearly 15 minutes after the release and the concentration peaks approximately 55 minutes after release. As in the first test, the concentration of SF_6 is greater in the main deck head than the first class quarters.

On 24 March the third test in this series was conducted and the results are presented in Figure 9. Again it can be seen that the concentration of SF_6 in the deck berthing compartment closely follows the concentration of SF_6 in the release compartment with a time lag of about 10 minutes. There are no noticeable levels of SF_6 in the remaining compartments until minute 55 when WTD 1-52-1 was opened. The graph shows that except for the deck berthing compartment the concentration of SF_6 was greatly reduced in all compartments. Consistent with the first two tests, the concentration of SF_6 in the main deck head was greater than the concentration in first class quarters.

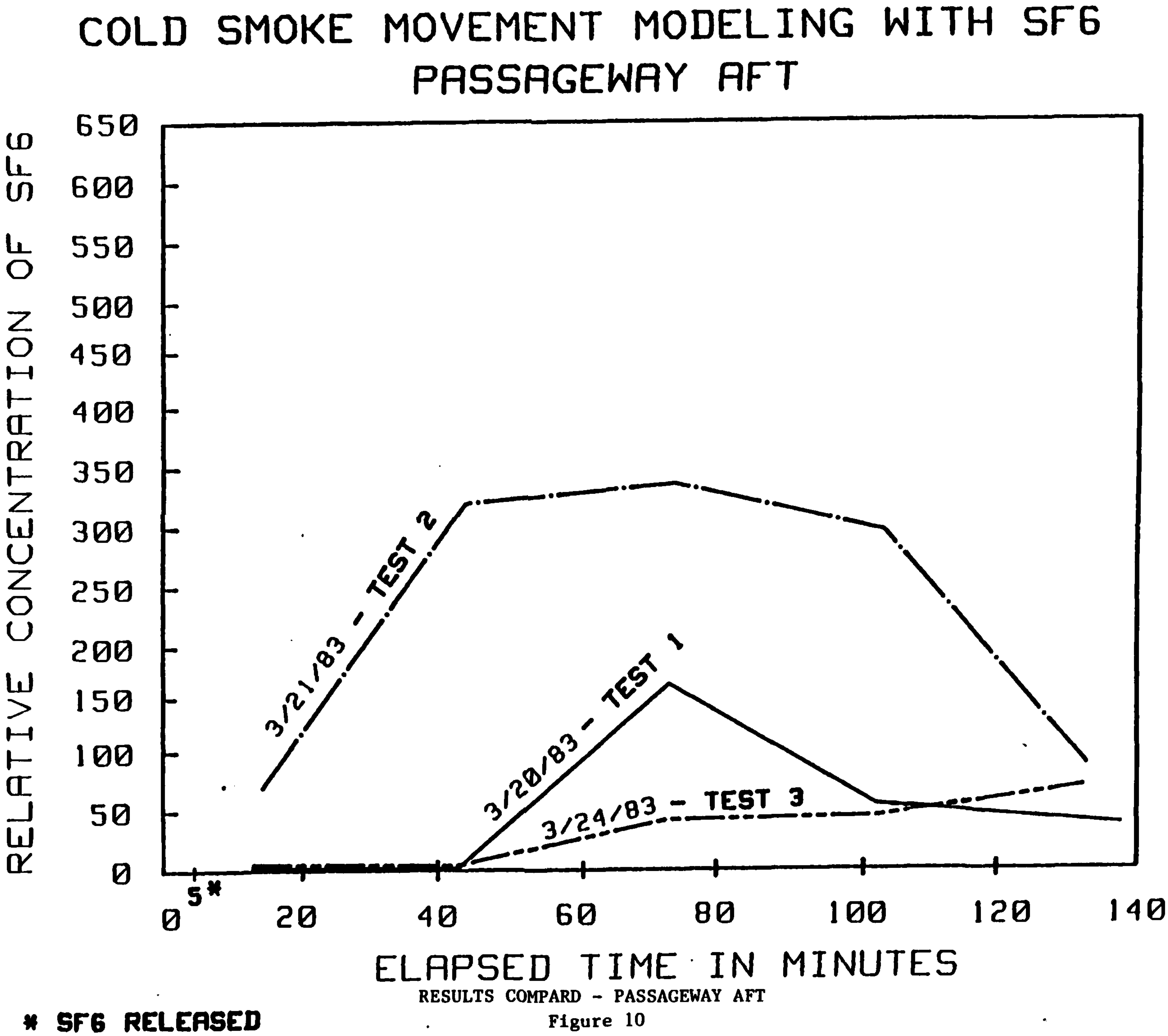
In order to illustrate the effects of the different closures and fan settings on a particular compartment, the results of the three tests are shown together. Figure 10 presents this information for the passageway aft. The graph displays what has been known for some time. If the door is closed, smoke will be contained. This graph tells quantitatively just how effective this simple act is. It shows that for the second test, where WTD 1-52-1 was left open for the entire test, the concentration of SF_6 steadily increased and remained high throughout the test until it dissipated. For the first test, where the WTD was closed until 55 minutes after the release and then opened for the remainder of the test, no detectable level of SF_6 was recorded until around 60 minutes after the release, then the concentration steadily increased but never reached the level that was achieved during the test where the door was never closed. In the third test, where the WTD was opened at minute 55 but closed after each opening, the concentration of SF_6 was reduced even further. It rose slightly reflecting the opening of the WTD but remained fairly constant. This was in spite of the fact that the WTD was opened a minimum of 100 times in the 85 minute period to allow the passage of people.

Similar results were obtained for the main deck head but concentrations differ. Figure 11 displays these results. For the first test, like the passageway aft, no detectable level of SF_6 was recorded until about 60 minutes after the SF_6 release. However, unlike the passageway aft, the concentration exceeded the level that was achieved during the second test where the door was never closed. The second test was similar to the second test for the passageway aft. The concentration rose steadily and remained constant until it dissipated. It differed from the second test for the passageway aft only in that the concentration was less. The third test results were similar to the third test results for the passageway aft in that the concentration of SF_6 was substantially reduced.

The results of the series of tests where the SF_6 was released from the paint locker are shown in Figures 12-15. Two sample locations, in addition to the release location, are graphically displayed to illustrate the results. Figure 12 displays the results of the first test of the paint locker series. The graph shows very little SF_6 detected at the sample locations in the passageway forward of the laundry and in the laundry until approximately

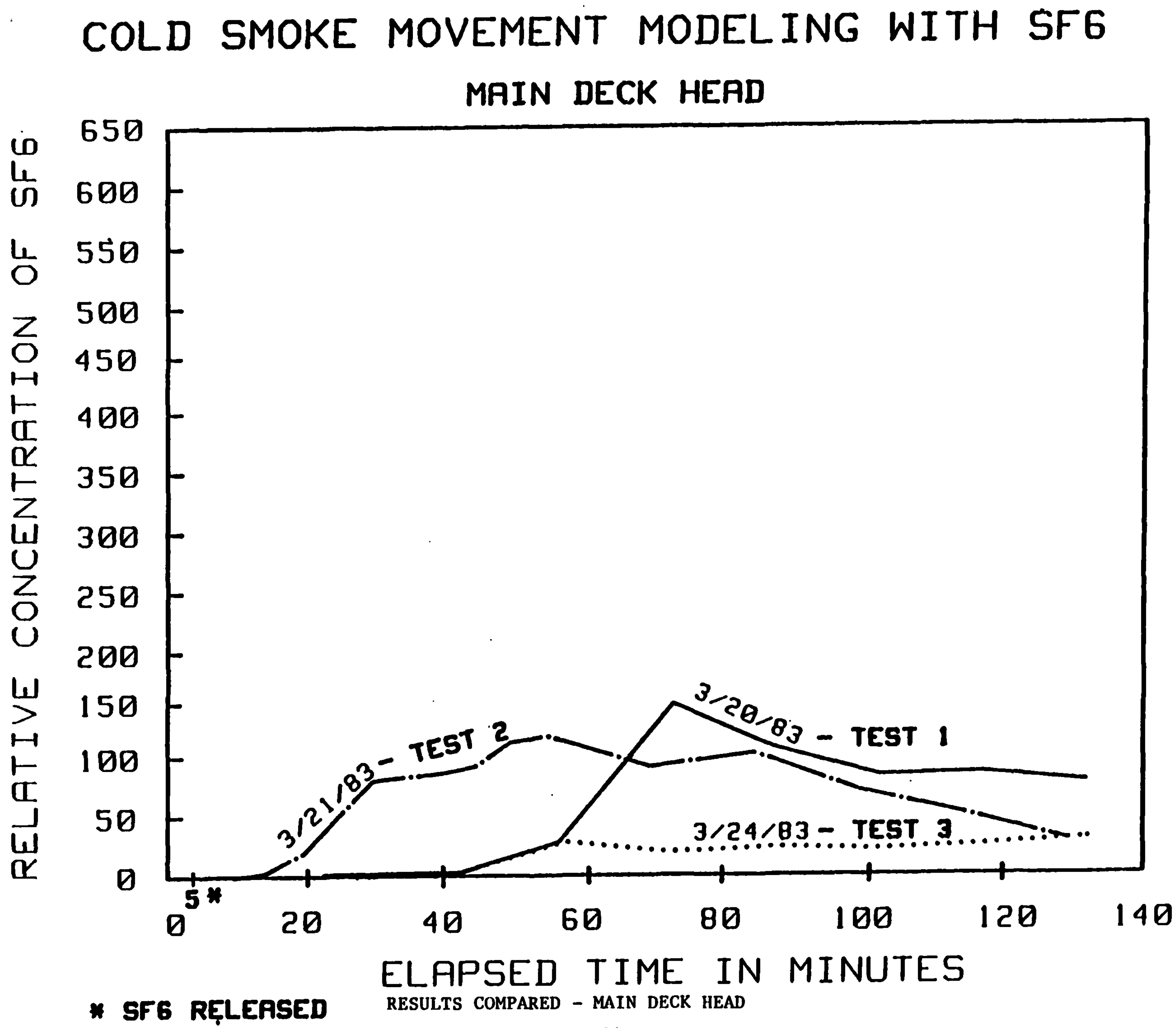


TEST 3 - BERTHING COMPARTMENT SERIES
Figure 9



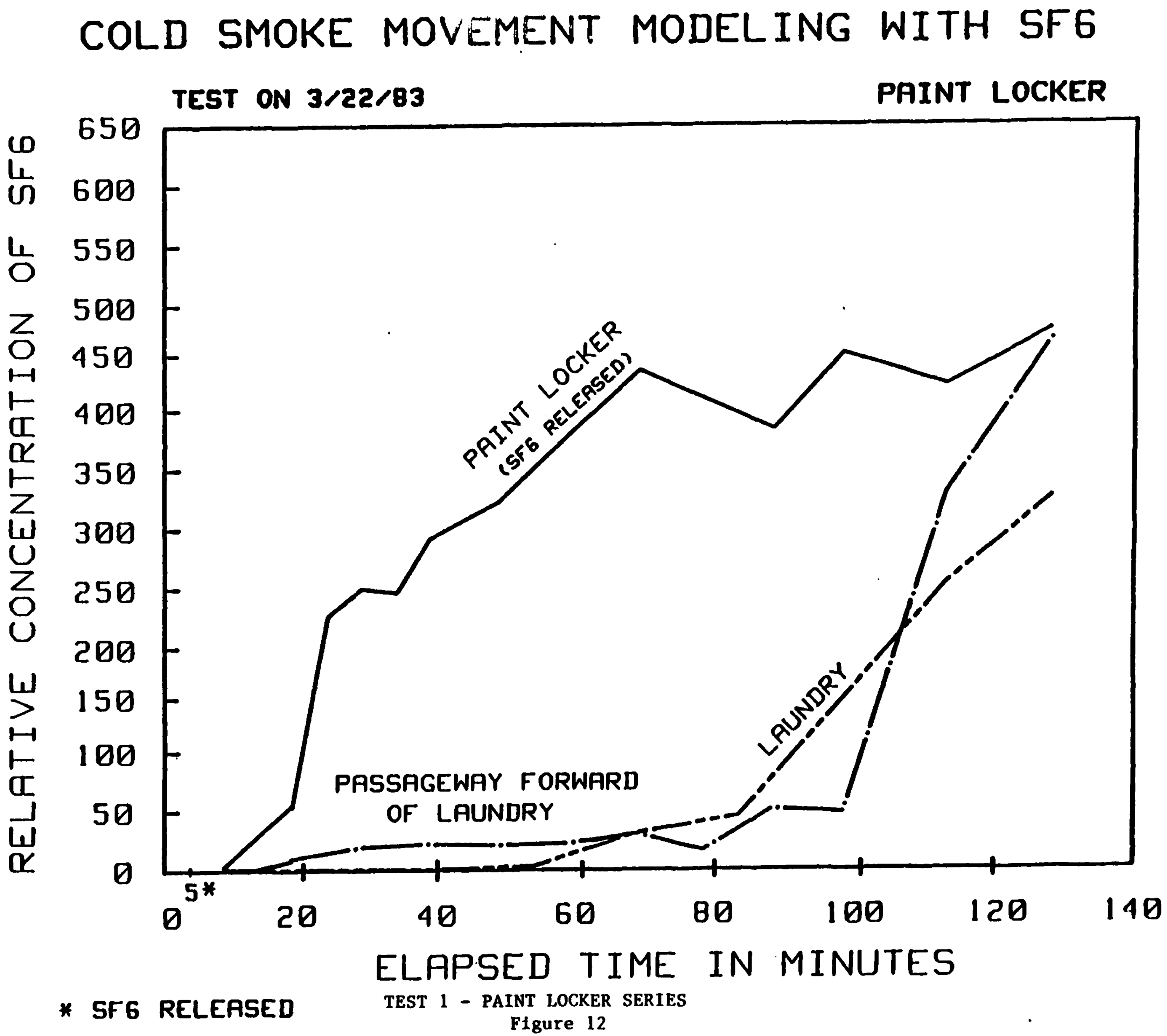
RESULTS COMPARD - PASSAGEWAY AFT

Figure 10

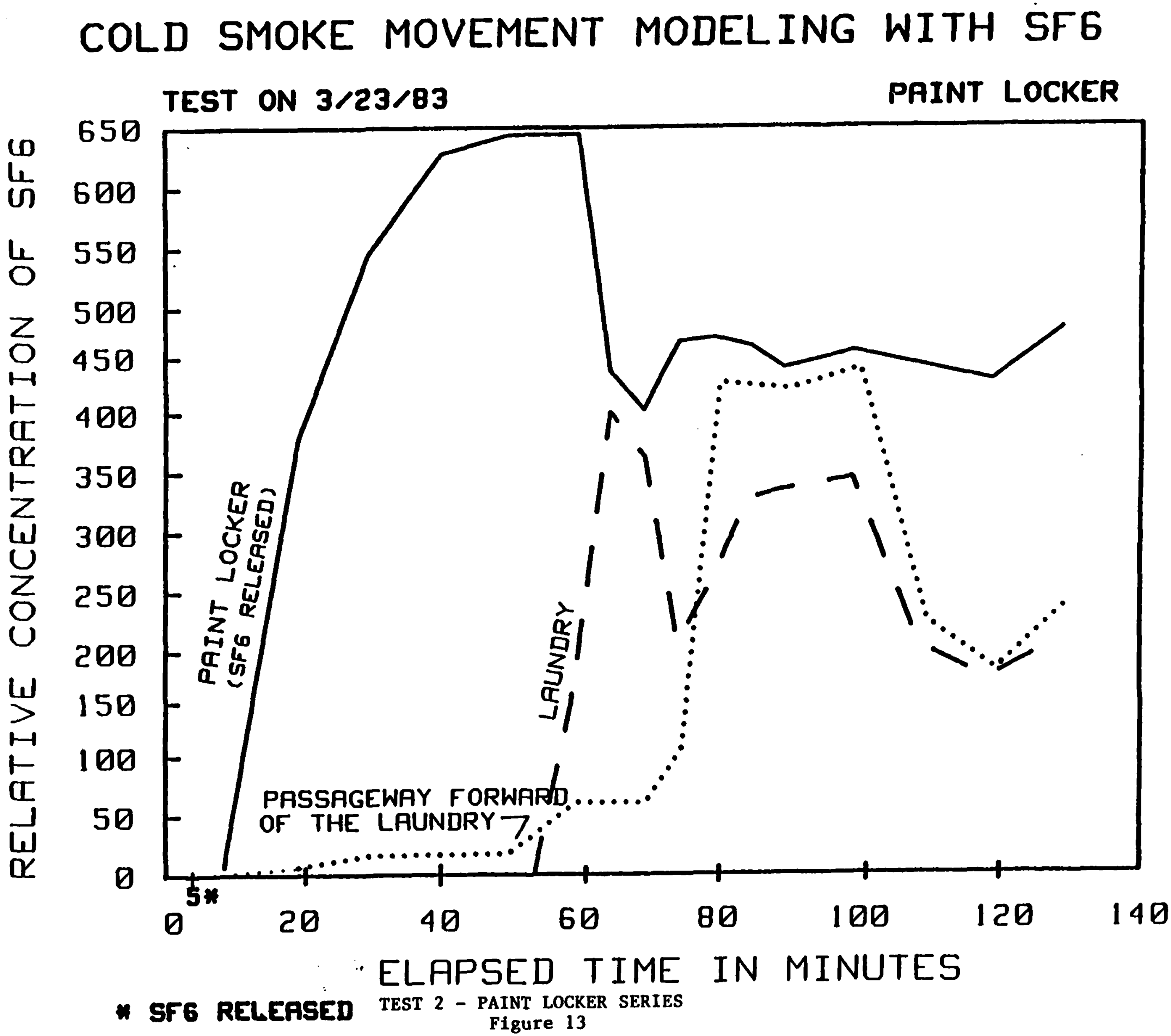


RESULTS COMPARED - MAIN DECK HEAD

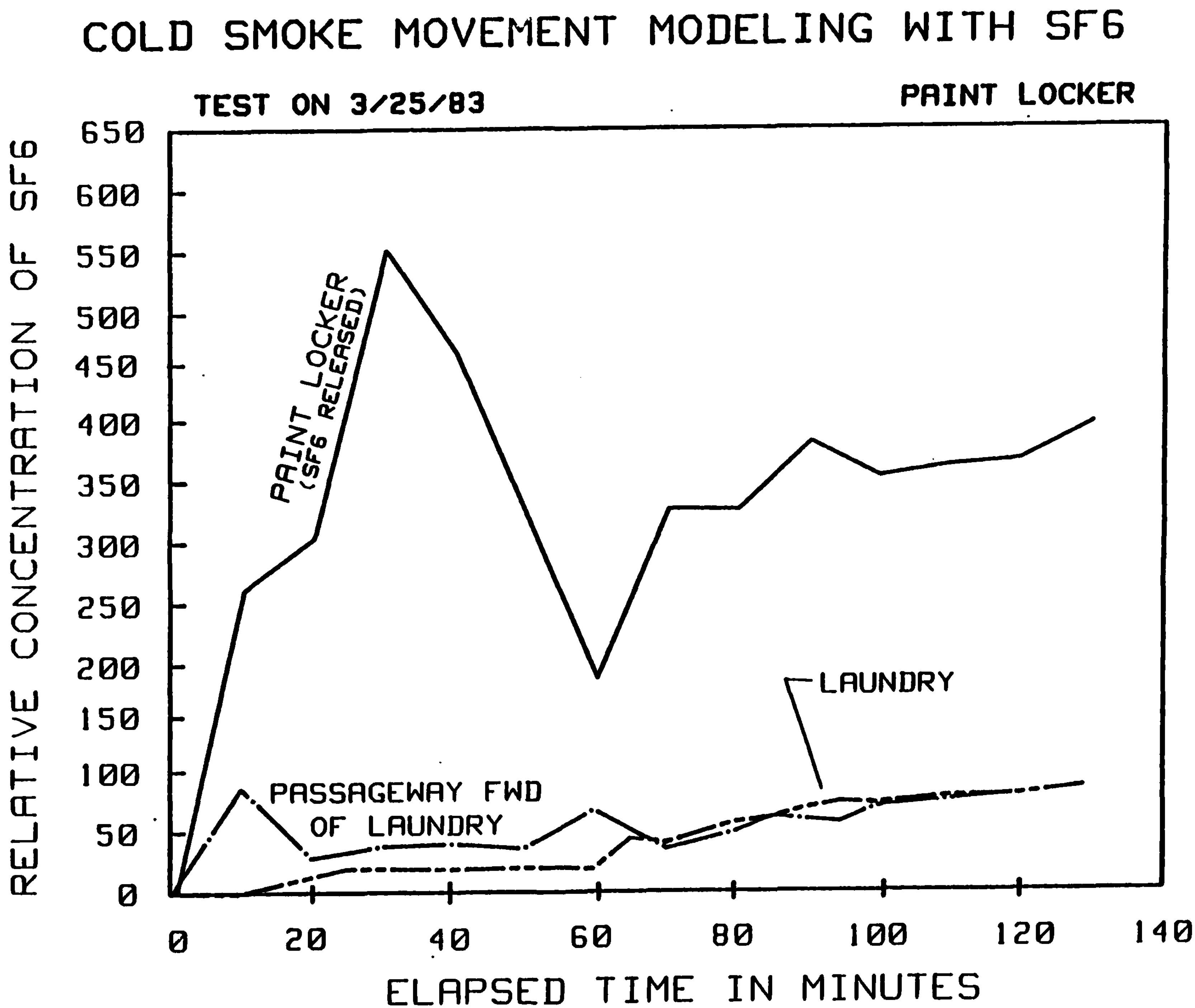
Figure 11



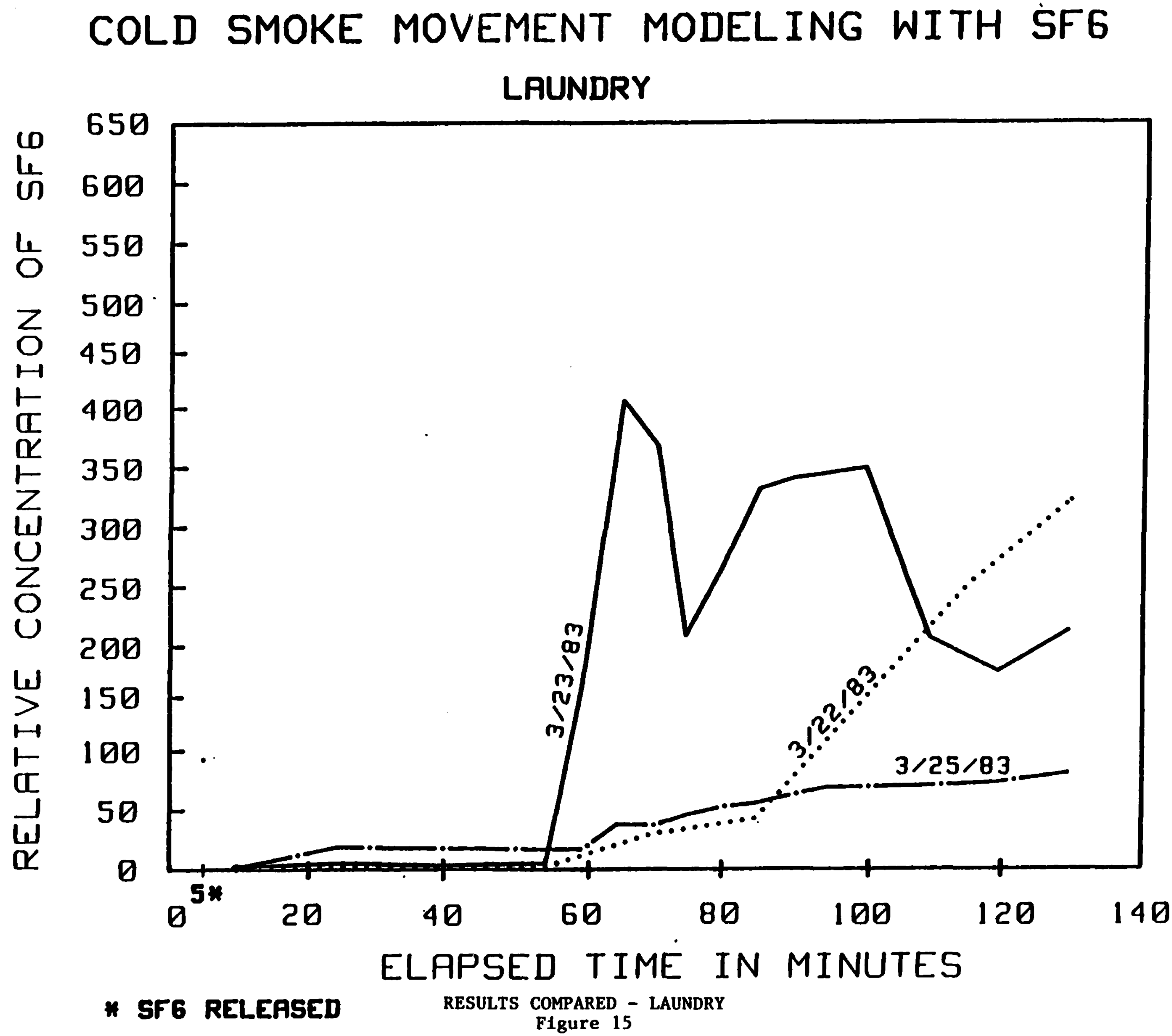
TEST 1 - PAINT LOCKER SERIES
Figure 12



TEST 2 - PAINT LOCKER SERIES
Figure 13



TEST 3 - PAINT LOCKER SERIES
Figure 14



RESULTS COMPARED - LAUNDRY
Figure 15

60 minutes after the release. It is first detected in the laundry. This was not what would be expected by sequentially following the SF_6 flow from the paint locker to the laundry. It would be expected to first appear in the passageway forward of the laundry. The SF_6 concentration curve for the passageway forward of the laundry behaves similarly to the curve for the laundry but lags it in time. It should be noted, however, that the concentration in the forward passageway does eventually exceed the concentration in the laundry.

The results of the second test of this series are shown in Figure 13. This test was run with the butterfly valve supply damper in the open position. As explained under Section 5.3, Paint Locker Series, WTD 1-20-1 was secured for the entire test. The paint locker was opened and the exhaust blower was engaged at about 50 minutes after the release. At around 60 minutes after the release the supply blower was restarted. The graph clearly shows the SF_6 found in the laundry before it is detected in the passageway forward of the laundry. The curve for the concentration of SF_6 in the laundry rises sharply at about 55 minutes after the release and the curve for the paint locker registers a corresponding drop. The same increase in the passageway forward of the laundry isn't observed until approximately 75 minutes after the release.

The third test run with the SF_6 released from the paint locker occurred on 25 March, and the results appear in Figure 14. Both WTD 1-20-1 and the butterfly valve damper were secured for the entire test. The graph shows that in both the laundry compartment and the passageway forward of the laundry, the concentration of SF_6 is noticeable but not significant. The results of the three tests were compared for the laundry and appear in Figure 15.

The graphs presented in this report are representative of results for the entire project. The raw numerical data for all segments of this test project will be maintained with the project file. Upon request, additional graphs can be constructed to study a particular sample location.

7.0 CONCLUSIONS

The objectives of this project have been successfully accomplished. Specifically:

1) A technique was developed that can determine the movement of air by using SF_6 as a tracer gas. The technique is transportable and field operational.

2) It was demonstrated under field conditions on an operational Coast Guard Cutter that the technique can provide quantitative data on air flow characteristics of ventilation systems.

The results from the initial work in pressure mapping indicate that the present ventilation system on the USCGC VIGOROUS is capable of providing the pressure difference required to control the movement of smoke. However, it is important to remember that these are preliminary findings and not conclusive. The results have not been verified nor have the tests been repeated. The pressure difference needed to control smoke movement was obtained across certain boundaries under specific closure positions and fan settings. It can not be concluded that these results could be obtained across all boundaries or all compartments.

This study used a tracer gas to follow the air movement. The results shown by the graphs in Figures 7-15 must be viewed with the limitation of these test conditions clearly in mind. Room temperature air was the fluid medium. The fluid medium in a fire situation would normally be hot combustion gases. The buoyant force from the hot gases would propel the smoke. Consequently, smoke would arrive in the compartments close to the origin of the fire sooner than the SF_6 was detected in these room temperature air tests. This should be kept in mind when noting the time lag differences that occured in both test series. However, the buoyant force diminishes as the distance from the fire increases. At the distance where the buoyant force becomes negligible the smoke is carried solely by normal air currents. Although this study followed normal air movement, it cannot be assumed that this accurately represents cold smoke movement. Sulfur hexafluoride was shown to respond very quickly to small changes in air currents. A molecule of SF_6 is a great deal smaller than a particle of smoke. This indicates that SF_6 is more responsive to small changes in air currents than smoke particulate matter would be. It might therefore be expected that smoke would arrive in compartments a great distance from the source of the fire later than the SF_6 would be detected.

Tests showed that air patterns were constant and results were reproducible. It can therefore be concluded that normal air transfer patterns are predictable.

Seven tests involved isolating and/or exhausting the tracer gas by manipulating the closure and fan speeds. The SF_6 was confined by two different methods. The first method simply used the ventilation system in a passive mode. That is, by securing the supply and exhaust fans, closing the dampers and setting the closures in the "General Quarters Configuration," SF_6 was confined to the release area. However, in order to fight a fire, a boundary must be opened for access. When a boundary was opened, SF_6 soon appeared in all open spaces. This limits the effectiveness of smoke confinement. Better confinement was achieved by using the ventilation system in an active mode. By creating a pressure differential such that the pressure outside the SF_6 release compartment was greater than that inside, any leaks were into the "contaminated" area thus enhancing the confinement. This pressure differential was obtained by either (1) exhausting the "contaminated" compartment with the supply damper closed while exhausting the surrounding compartments with the supply dampers open, or (2) exhausting the "contaminated" compartment with the supply damper closed while exhausting and supplying the surrounding compartments. The additional increase in pressure difference created by engaging the supply blower resulted in an insignificant increase in the amount of SF_6 confined. However, there were too few tests conducted and there is insufficient data to conclude at this time that one method of creating the pressure differential is better than the other method.

It was mentioned above that when a boundary was opened, SF_6 appeared in all open spaces. The SF_6 was minimized in these spaces when the water tight door was closed each time after opening and thus the boundary was reestablished. In an actual fire, it is often neither practical nor possible to keep closing doors. Firefighters, damage control teams and repair parties require immediate access to the fire. Fire hoses and other lines must frequently run through a number of compartments. Consideration should be given to alternative methods to confine smoke such as smoke curtains and access holes for fire hoses.

The important role that dampers can play was dramatically shown in the series with the SF_6 released from the paint locker. Immediately upon starting the exhaust system to vent the paint locker, SF_6 appeared in heavy concentrations in the laundry. Since the normal path firefighters would take in responding to a fire in the paint locker is through the laundry, a heavy concentration of smoke in the laundry would hinder response and aggravate an already serious incident. It can be concluded that the closure of the butterfly valve to the paint locker is critical for the confinement of smoke to that compartment.

It should be mentioned that the vessel's position with relation to wind direction is important whenever the supply lines are open. If the relative wind were off the port side of a medium endurance cutter, smoke could be blown across the ship, be taken in the supply intake, and distributed throughout the forward areas of the ship. Unless it was closed, smoke exiting the main deck exhaust outlet might enter the intake and be distributed throughout 01 and 02 decks via the supply ducts.

The SF_6 tracer gas technique can be used simply and quickly to test the watertight integrity of any compartment on any Coast Guard vessel. The technique can also be used to identify critical areas in current ventilation systems. Thus it could be used as developed to continue the work on the medium endurance cutters or it could be applied to other classes of cutters.

It can be concluded that this rather inexpensive technique is a powerful tool with much potential in several areas pertaining to vessel analysis and modification. Studying one vessel and incorporating improvements in an entire class of vessels also makes it very cost effective.

8.0 RECOMMENDATIONS

It is recommended that further work be done in the area of pressure mapping. The preliminary work was encouraging and indicated that the present ventilation system might be capable of creating the required pressure differences. However, the work was too limited in scope and the results were not conclusive. Additional testing is needed to determine the limits of the ventilation system's capability. It is necessary to ascertain which compartments could contain smoke or be used as escape routes through manipulation of closures and fan settings as well as those compartments that cannot.

For those compartments where pressure differentials can be created that are sufficient to control smoke movement, additional work is recommended. The required pressure differential might be created by a number of different combinations of closure positions and fan settings. Additional work could identify the most efficient method and provide alternative combinations should one be required.

It is recommended that more work be done on the medium endurance cutters. Only two of the supply ventilation systems have been looked at in this study.

It would not be feasible to study all of the systems. For example, the engine room has so many sources of ventilation that to study the ventilation system that services it would be impractical from the view point of smoke confinement. It is recommended, however, that some of the other ventilation systems, particularly the systems servicing accommodation areas, be studied. Special emphasis should be placed on the use of dampers. In cooperation with naval engineering personnel in Coast Guard Headquarters, specific areas could be selected and/or other classes of cutters could be examined.

More importantly, it is recommended that further work be done with the technique since it shows strong prospects for evaluating smoke control systems on ships. Presently, the technique is valid only for cold flow air movements. Correlation factors between hot smoke flow and cold air flow need to be identified and criteria developed to relate the two. Future work would attempt to closer simulate a hot flow condition.

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